BBC RD 1984/6

RESEARCH DEPARTMENT

REPORT

The present status of Clean PAL systems

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July 1984

BBC RD 1984/6
UDC 621.397.132.125

THE PRESENT STATUS OF CLEAN PAL SYSTEMS

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Summary

The various approaches to realising a Clean PAL system, in which luminance and chrominance interact minimally, are reviewed. Attention is focussed on the Weston Clean PAL system which offers the possibility of simultaneous luminance and chrominance transmission retaining the optimum spectral distribution for each. Starting with the original proposal, based on single line delay filters, it is shown how the system can be refined using more complex filters or enhanced, using an auxiliary signal to carry the lost information. The relationship with MAC is also discussed, and it is shown that, using the most complex filters, a vertical chrominance performance superior to MAC can be obtained.

Issued under the Authority of

M.E.B. Moffat

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

July, 1984
(PH-258)

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THE PRESENT STATUS OF CLEAN PAL SYSTEMS

Original concept of Clean PAL invented

1973

1974

Demonstration of line-based, band-segregated Clean PAL
Development of 3D spectral models and accommodation with sub-Nyquist PAL

1975

Report 1975/36 on band-segregated Clean PAL

Early appraisal of 313-line delay sub-Nyquist PAL

1976

Incompatibility of line-based Clean PAL and sub-Nyquist PAL

1977

Weston Clean PAL discovered
Designs Department proposals for PAL coding and decoding
Incompatibility of line-based Weston Clean PAL and sub-Nyquist PAL predicted

Subjective assessment of line-based Weston Clean PAL with/without sub-Nyquist PAL
Theoretical comparison of line-based PAL decoders

1978

Subjective comparison of line-based PAL coders
Comparison of Weston Clean PAL and notched PAL with and without sub-Nyquist PAL

Patent on Weston Clean PAL filed. Demonstration at IEE along with Philips band-segregated PAL system

1979

Report 1980/1 on Weston Clean PAL. Lecture at RTS along with Questech PAL decoder

1980

Internal demonstration of Clean PAL

1981

Wells-Weston Clean PAL proposed internally for DBS
Weston EPAL proposed internally for DBS

Demonstration of Wells-Weston Clean PAL

1982

Demonstration of high-order luminance filtering on Computer Image Processor
Explanation of Weston Clean PAL as quadrature modulation
Investigation into MAC chrominance

Weston Clean PAL proposed for DBS centre and rejected

1983

THE PRESENT STATUS OF CLEAN PAL SYSTEMS

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1. Introduction

The PAL colour television system is a method of coding the luminance *(Y)* and colour difference components *(U, V)* into a single signal in which the colour difference signals share part of the frequency band of the luminance. As a result, when the signal is decoded in the conventional way, there is some crosstalk from luminance to chrominance and vice versa. The luminance to chrominance crosstalk is known as cross-colour and appears as coarse 'rainbow' patterns or random colours in areas of fine detail. The chrominance to luminance crosstalk is known as cross-luminance and appears as a fine pattern on chrominance edges which are substantially vertical.

Fortunately, the nature of real pictures is such that such cross-effects are generally not present and rarely impair a television programme; however, when they are noticed they can be irritating. To reduce or eliminate these cross effects various modified PAL systems have been proposed. They invariably involve modifying both the PAL coder and the decoder in order to obtain maximum benefit and such systems have become known as Clean PAL systems. This Report traces the development of these systems and suggests a course for future work.

2. System Alternatives

About 10 years ago, an attempt at mitigating the cross effects was made by Lent and Reed[1]. This investigated the effect on cross-colour of introducing various filters in the coder luminance path (actually in the luminance channel of a four-tube camera which was then matrixed to RGB before PAL coding). The problem of cross-colour had already been anticipated when the PAL system specification was drawn up and provision exists in the specification for the inclusion of a notch filter in the coder luminance path. This attenuates luminance frequencies in the region surrounding the subcarrier frequency by a maximum of 6 dB, having a 3 dB width of 400 kHz. While this attenuates the worst cross-colour, it does not cure the problem completely as cross-colour is still caused by those luminance components outside the notched band but inside the decoder's chrominance band. Clearly the result depends on the characteristics of both the coder and the decoder but it can be argued that it is the most sensible solution for the conventional receiver since the notch filter in the decoder, which partly suppresses cross-luminance, prevents the luminance components near subcarrier frequency being seen anyway. The experiments of Lent and Reed confirmed that introducing progressively more filtering in the luminance at the coder reduced the cross-colour correspondingly. However, the use of a luminance notch filter in the coder has been seen to reduce picture sharpness slightly, under certain circumstances.

The introduction of coder notch filters could be called a one-dimensional approach since the filter only responds to the signal frequency and takes no account of the nature of the spatial and/or temporal frequency in the image represented by the signal frequency. The relationship between signal frequency and spatial frequency, which has horizontal and vertical components, was first shown by Mertz and Gray[2] and enables the discussion to be based on the two-dimensional spectrum of the image and the coded PAL signal. Using this representation it is possible to gain insight into the kind of filters that are more selective in their action and enable a better balance in the spectral distribution of the received signals to be obtained.

The first attempt to base a system on filtering in more than one dimension was made by Drewery[3]. As this was designed to attack the problem of chrominance to luminance crosstalk, which he termed cross-luminance, as well as cross-colour, it became known as a Clean PAL system. The method was based on the idea of dividing the high horizontal frequency part of the two-dimensional spectral space into distinct bands of vertical frequency and allocating only luminance or chrominance to each band. In practice, this band-segregation approach proved unacceptable because it resulted in very low vertical bandwidth for the chrominance and high frequency luminance. Thus it was not much of an improvement over the extreme form of the one-dimensional approach, investigated by Lent and Reed, in which the luminance would be simply low-pass filtered to avoid the chrominance band altogether. Moreover, complete elimination of luminance/chrominance cross-effects required infinitely sharp-cut vertical filters.

However, Drewery also extended the theory of Mertz and Gray to three dimensions by including the image temporal frequency (i.e.

motion). The extra degree of freedom conferred by a third spectral dimension gave a significant increase in the vertical bandwidth that could be recovered from a band-segregated system though at the expense of motion portrayal since filters based on field-delays were involved. Although the three dimensional form was considered impractical, because of the high cost involved at the time, some years later, it was applied to the decoding of moving pictures for an electronic stills store[4].

A further difficulty with the two-dimensional form of Clean PAL was that it was incompatible with sub-Nyquist sampling of the PAL signal* which had just been proposed as a method of reducing the bit rate of digitally encoded PAL[5]. This technique was so successful that it began to be used as a *sine qua non* for future digital developments in PAL transmission. As a result, two-dimensional, band-segregated Clean PAL was abandoned but it is possible that three-dimensional, band-segregated Clean PAL could be made compatible with sub-Nyquist PAL.

Interest in a cheap (one- or two-dimensional) solution to the Clean PAL problem then waned until it was discovered that a system could be based on the international digital exchange system proposed by Weston[6]. This system, schematically shown in Fig. 1, was designed to allow PAL countries to exchange programmes via an intermediate digital signal consisting of luminance, sampled at twice the subcarrier frequency ($2f_{sc}$), and 'composite' chrominance sampled at f_{sc} and consisting of $U + V$ and $U - V$ on alternate lines. This signal may be termed W for convenience.

An important property of the system is that the PAL signal assembled from the components of a W signal, itself derived by splitting a PAL signal, is identical to the original PAL signal, i.e. the route PAL-W-PAL' is transparent. On the other hand, countries generating YUV signals could also

* British Patent 1511230

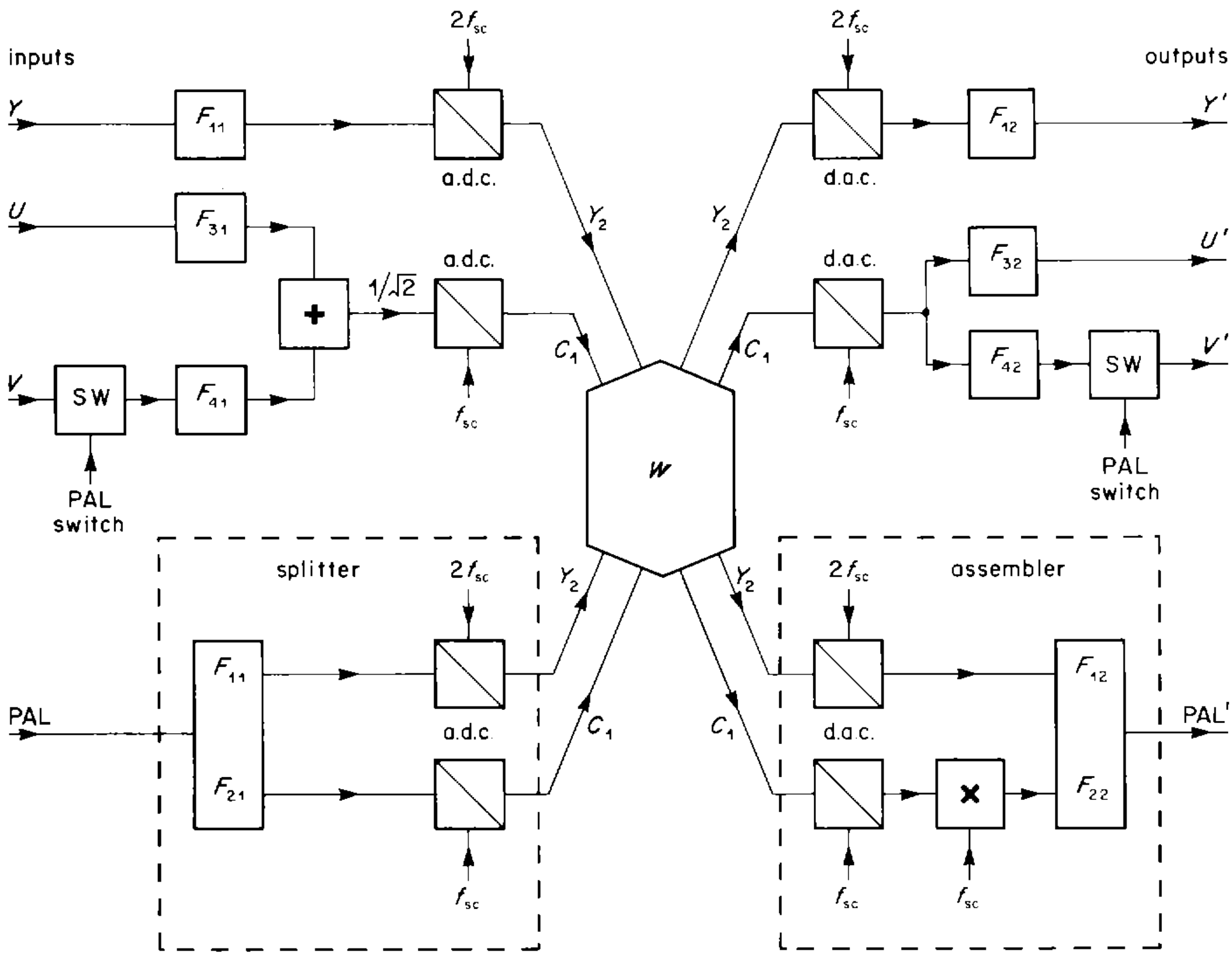


Fig. 1(a) – General schematic of the Weston exchange system for international digital connections.

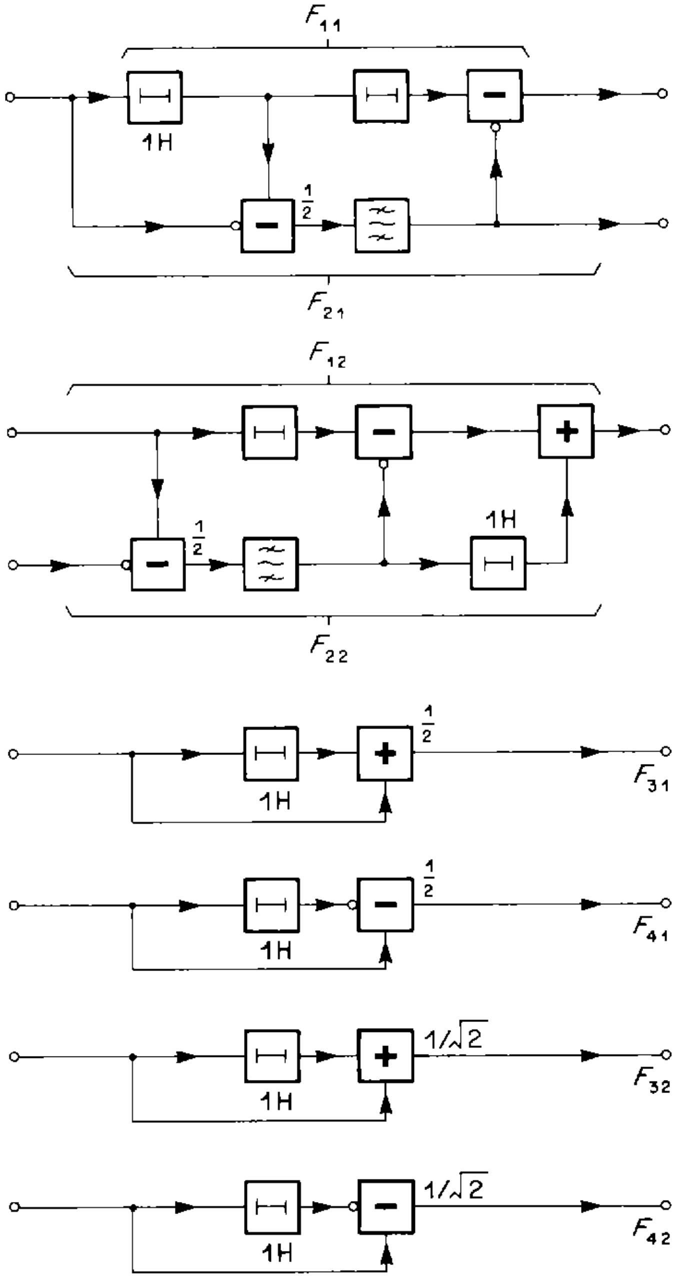


Fig. 1(b) — Details of the filters referred to in Fig. 1(a).

exchange programmes via the *W* signal although in this case there would be some impairment to the received *YUV* signals because they contain, in total, more information than the *W* signal can convey. Nevertheless, the impairments in the received *YUV* signals, in the form of luminance aliasing and *UV* crosstalk, were judged slight and negligible compared with those incurred by subsequent SECAM coding and decoding.

Clearly it would also be possible for a PAL country to exchange programmes with a *YUV* country using the routes PAL-*W*-*YUV'* or *YUV*-*W*-PAL' with acceptable quality. However, it was subsequently realised that PAL derived from *YUV* via the system could be converted back to *YUV* via an identical system and the *YUV* so derived would suffer no luminance/chrominance cross-effects. That is, the route *YUV*-*W*-PAL'-PAL-*W*-*YUV'* is equivalent to the route *YUV*-*W*-*YUV'* because the route PAL-W-PAL' -PAL-*W*-PAL' and therefore *W*-PAL'-PAL-*W* is transparent. In the route *YUV*-*W*-*YUV'* the *Y* and *U*, *V* signals do not interact, and thus the system offered a means of clean coding and decoding.

This Clean PAL system did not depend on spectral segregation since it could be shown that the *Y*, *U* and *V* spectra overlapped considerably in the chrominance band. Thus perfect luminance/chrominance separation did not depend on perfect vertical filters. Moreover, the system offered twice the usable vertical bandwidth of the band-segregated two-dimensional method. Unfortunately, when combined with sub-Nyquist sampling of the PAL signal, theory showed that the received *YUV* signals suffered further resolution loss and that a slight amount of crosstalk was reintroduced. This was later confirmed by experiment.

At about the same time, some other ideas for PAL decoding were proposed by Auty, Read and Roe at BBC Designs Department*. These involved treating only the luminance path at the decoder to attack the problem of cross-luminance but the techniques could also be applied at the coder** to reduce cross-colour[7]. They were based on the idea of using a signal from the adjacent line or lines to cancel cross-luminance (at the decoder). Previously this had been thought impossible because the subcarrier phase and *V*-axis switch for the adjacent lines are inappropriate for any given line. However, the new techniques involved the use of a PAL modifier to reverse the V-axis switch and alter the subcarrier phase. Although this enabled the chrominance part of the PAL to be dealt with, the introduction of the modifier also created a spurious luminance signal similar to that in the Weston system, though of different magnitude. After some initial discussion, four variants of the technique were proposed based on one or two adjacent lines and having zero or 6 dB attenuation of the high frequency luminance.

Although the Weston Clean PAL system and the Designs Department systems appeared to have little in common, the one being based on a digital

*British Patent Application 22567/77. **British Patent 1586741.

signal and the others analogue, it was shown by Clarke[8] that the decoder circuits of the proposals could be re-arranged in analogue form to show a high degree of commonality. Analysis of the systems showed that the Designs Department proposals suffered from either a 6 dB overload, caused by the interaction of the wanted luminance with the spurious luminance alias for some critical situations, or a uniform 6 dB attenuation of the wanted luminance. Subjective comparison of the coders by Oliphant confirmed that the Weston coder was preferred to any of the Designs Department versions and also to a notched PAL coder for colour pictures, although being equal to a notched coder for compatible monochrome pictures. Attention was therefore directed to the Weston system as offering the best solution to the Clean PAL problem, although not necessarily to the problem of decoding normal PAL.

The Weston Clean PAL system was examined closely by Oliphant[9], including comparison of the coder with a notched coder with and without sub-Nyquist PAL coding. The conclusion reached was that the improvement the system offered was worthwhile, most benefit being derived from using the clean coder. This took into account the drawbacks of the luminance aliasing and *UV* crosstalk necessarily introduced by the system and which had been judged acceptable when the exchange system had first been derived. As a result, patent protection was applied for* and the system was demonstrated at the I.E.E. in 1979 jointly with a system developed by Philips, based on the earlier, band-segregated ideas. These demonstrations created such an interest in improved PAL coding that a public tutorial on Clean PAL was given a year later together with a demonstration of an adaptive decoder developed by Questech, based on the Weston system.

At about this time (1980) Designs Department were seeking improvements to add to a new generation of PAL coders and a decision to incorporate such techniques as Clean PAL coding would have far-reaching consequences. Accordingly, the Weston system was again demonstrated internally to assist such a decision. Unfortunately the issue, by then, was complicated by the fact that variants of the system had been derived, using filters based on 313-line or 625-line delays. Only a decoder based on these variants had been built and so the performance of a complete system based on field or picture delays had to be inferred from that of the decoder[10]. Taking into account the various combinations of normal and clean processing at either or both ends of the system, coupled with the number of system variants, the demonstration was inevitably complex. The upshot of the demonstration was that it was decided not to implement Weston Clean PAL. The line-based (two-dimensional) version was not thought to offer a significant increase in quality, given the drawbacks of luminance aliasing and *UV* crosstalk, and the cost of introducing such a Clean PAL system also weighed heavily upon the deliberations. The field and picture-based versions were thought to be impracticable at that time and, it could be argued, developments were in the pipeline which might undercut any decision. Besides, there remained the incompatibility with sub-Nyquist PAL.

3. Clean PAL and DBS

The issue of Clean PAL next emerged in the context of Direct Broadcasting by Satellite (DBS). The compromises adopted in EPAL (Extended PAL)[11] which caused cross-luminance and cross-colour to appear at the lower edge of the chrominance band prompted the proposal of an alternative EPAL based on Weston Clean PAL*. In this technique the *YUV* would be first coded into Clean PAL which could be decoded either by conventional or clean means. In addition, the residual signals corresponding to the impairments of the clean system would be combined into an auxiliary signal and combined above the video frequency band with the Clean PAL signal in much the same way as in the EPAL signal. A modified EPAL decoder would then extract the auxiliary signal, split it into its component *YUV* residuals and add them to the cleanly decoded *YUV* to produce *YUV* free from resolution loss, luminance aliasing and *UV* crosstalk. In this way, it was argued, the conventional receiver would give a sharper picture, since the luminance would be comb-filtered instead of low-pass filtered; meanwhile the EPAL receiver would obtain a noise improvement because the auxiliary signal would lose the high-frequency luminance of low vertical frequency (which would travel in the clean signal) in exchange for chrominance of high vertical frequency. The technique was known as Compensated Weston Clean PAL.

At about the same time, as a result of investigations into sub-Nyquist sampling of PAL using field- and picture-delay-based filters[12] Wells proposed the use of a mixed Clean PAL system for DBS based on picture delays for the luminance and high-order vertical filtering for the chrominance.

* British Patent 2044577.

* British Patent Application No. 8201760.

Wells claimed that the sub-Nyquist PAL experiments showed that observers could not see the effects of the temporal filtering on the luminance but only on the chrominance. Since the impairments of the sub-Nyquist system are similar to those of the Weston Clean PAL system, he reasoned that an acceptable Clean PAL system would therefore be obtained with picture-delay filtering of the luminance provided the *UV* cross-talk could be overcome by purely spatial filtering. It had been recognised from the outset that mixed systems involving different kinds of filtering for luminance and chrominance were possible and that the aliasing and crosstalk could be reduced by using sharper filters. Yet it was generally believed that it was the chrominance which could be filtered temporally without undue subjective impairment whilst the luminance would suffer more by temporal filtering.

A simulation of Clean PAL based on Wells' principle was, nevertheless, built and demonstrated. The luminance filtering was based on picture delays and the chrominance pre- and post-filters were each seventh order vertical (taking contributions from eight adjacent field lines). These had been designed so as to give a balance between maximising the spectrum of the wanted signal and minimising the spectrum of the unwanted signal consistent with acceptable edge ringing and crosstalk amplitude in the time domain. Sufficient hardware was built to simulate the complete system, using the *YUV-W-YUV'* path, or to realise the coder.

The results of the demonstration were impressive. Using critical picture material, the UV crosstalk was rendered imperceptible without noticeable vertical chrominance ringing and the chrominance vertical resolution loss was just perceptible. On movement the luminance aliasing was imperceptible and the resolution loss was masked by camera integration for all but a critical range of speeds near the subcarrier dot-crawl speed. Even then, it was difficult to perceive the loss. The conclusion reached was that the system offered a useful alternative to EPAL, although it was obviously much more complex instrumentally.

4. Further Development of Clean PAL

The benefit of high-order vertical filtering having been demonstrated for the chrominance, a similar exercise was carried out on the luminance as an alternative method of eliminating the aliasing, avoiding temporal filtering. This was done on a computer-based image processor which could handle only still pictures. The advantage of using the computer was that the filtering was not restricted to pure vertical cascaded with a horizontal band pass filter (variables separable) but could be any arbitrary two-dimensional characteristic. An idealised characteristic was chosen as in Fig. 2 which maximised the spectral

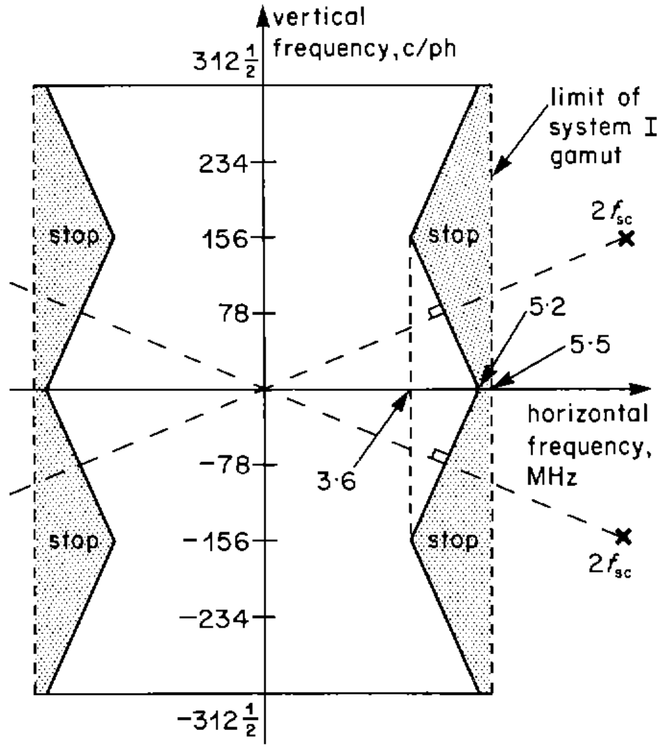


Fig. 2 — The idealised two-dimensional frequency characteristic of the optimum luminance filter.

energy near the origin, consistent with allowing the spectrum to repeat at multiples of the $2f_{sc}$ sampling frequency. Using a 22 (horizontal) x 4 (vertical) - term filter a sufficiently sharp cut could be obtained to give negligible aliasing whilst retaining about the same spectral area as the simple first-order vertical system. Ringing was just perceptible on diagonals of critical material. Thus the second major objection to the Weston Clean PAL system had been overcome.

The use of mixed filtering for luminance and chrominance allows them to be separately optimised whilst still occupying the same spectral space as shown in Fig. 3. The disadvantage is that as the chrominance and luminance spectra are no longer complementary they cannot share the same filters and so the circuitry becomes more complex. Nevertheless, such separate processing provides an optimum package for *YUV* signals which is very relevant to transmission systems. In comparing *YUV* packages for bit-rate reduction, Wells was struck by the efficiency of Clean PAL and showed

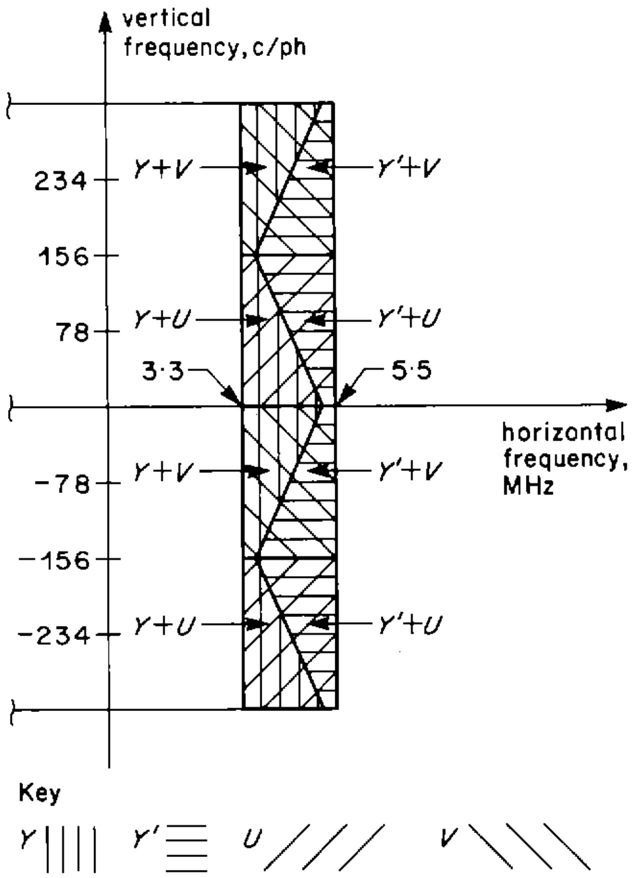


Fig. 3 — The two-dimensional spectral form of the idealised Clean PAL signal, showing the spectral overlap of Y, U and V.

that the mechanism whereby the combined chrominance and high-frequency luminance could share the same spectral space was entirely analogous to quadrature modulation. The wanted luminance, together with its repeated spectrum centred on the $2f_{sc}$ sampling frequency, could be considered as modulating one phase of the sub-carrier, the combined chrominance modulating the quadrature phase. This is shown in Fig. 4 for a simple low-pass filtered luminance signal. The function of the assembler circuit in the coder (Fig.1) is merely to enable the combination to resemble a PAL signal by introducing a further quadrature shift between *U* and *V* signals. This might not be needed for an internal *YUV* distribution system. Similarly, the function of the splitter in the decoder (Fig. 1) is to remove the quadrature shift between *U* and *V* in PAL and restore the quadrature relationship between luminance and chrominance, so that they can be separated by synchronous demodulation.

This way of looking at the Clean PAL system made it possible to see how to increase the horizontal bandwidth of the chrominance which hitherto had been restricted to 1.1 MHz, being that defined by the bandpass filters in the assembler and splitter. It was only necessary to widen these filters to encompass the appropriate chrominance bandwidth and such filtering would have no effect on the cleanly decoded luminance (due to the assembler/splitter transparency) although the comb filtering in the coder assembler would affect more of the luminance produced by a normal decoder. The only penalty would be an increase in the bandwidth of the composite Clean PAL, for the upper sideband of the subcarrier would have to be present, containing both combined chrominance and reflected luminance as shown in Fig. 4. In spite of this increase, the average horizontal bandwidth of the luminance would still be only f_{sc} as should be apparent from Fig. 2.

5. Clean PAL and MAC

Confirmation of the efficacy of high-order vertical filtering in improving the chrominance performance came from investigations into the

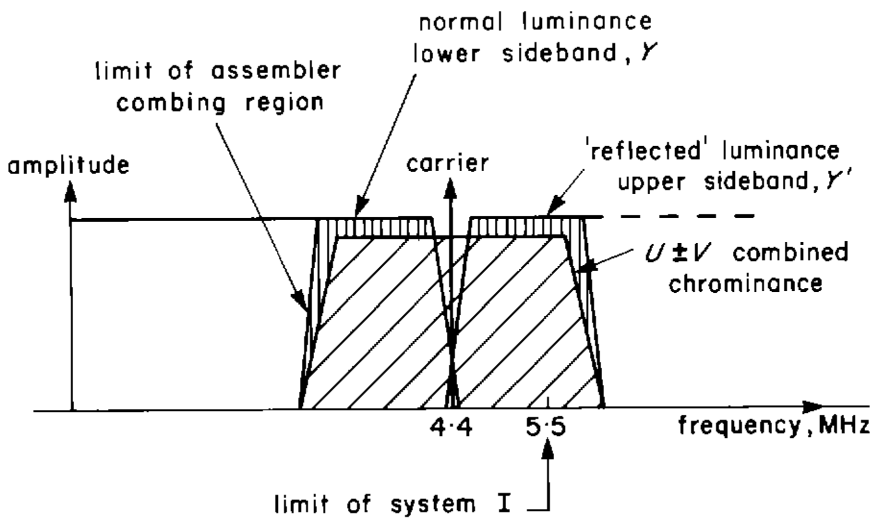
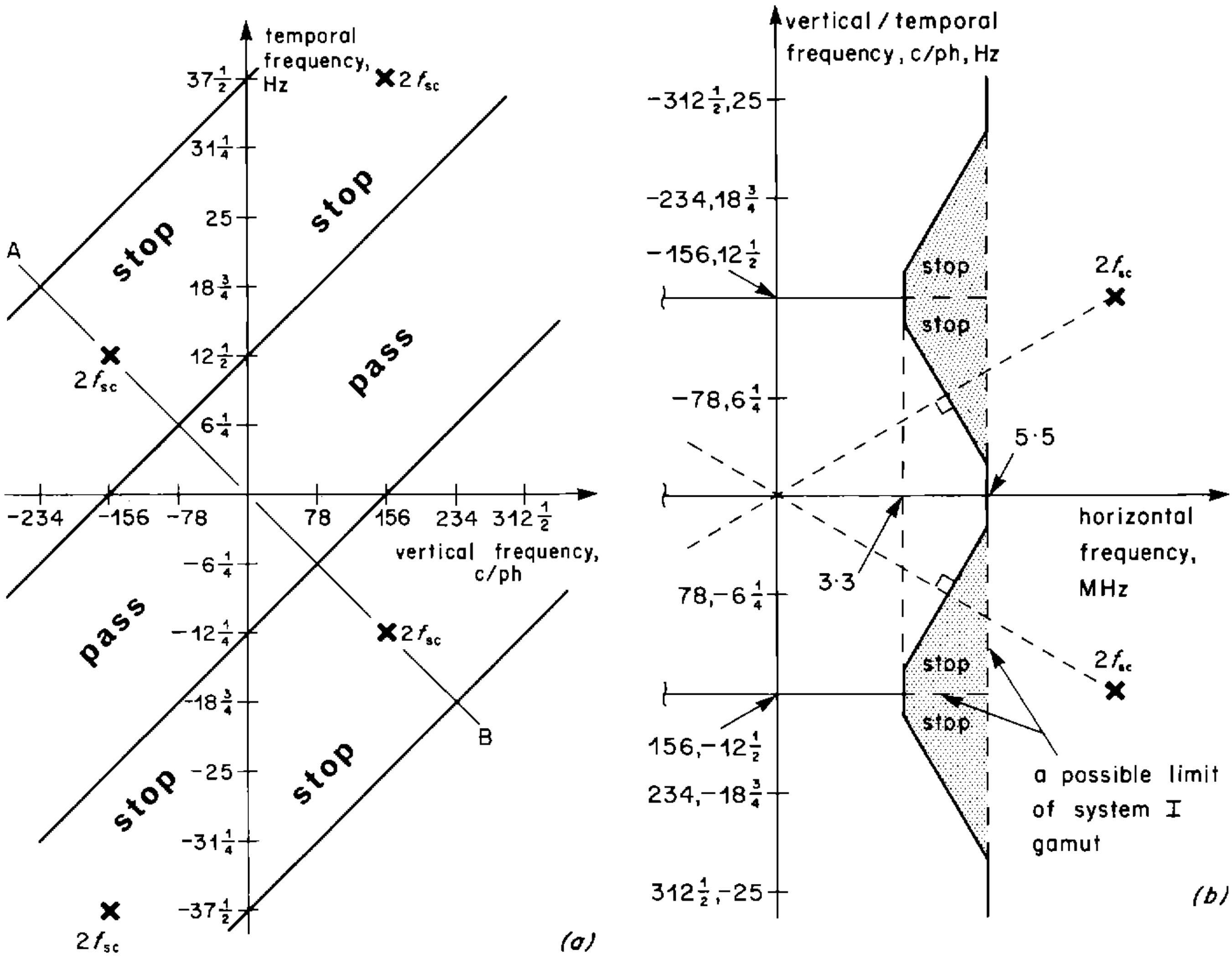


Fig. 4 — The one-dimensional spectral form of Clean PAL for one-dimensionally filtered luminance showing the double sideband nature of the luminance and chrominance.



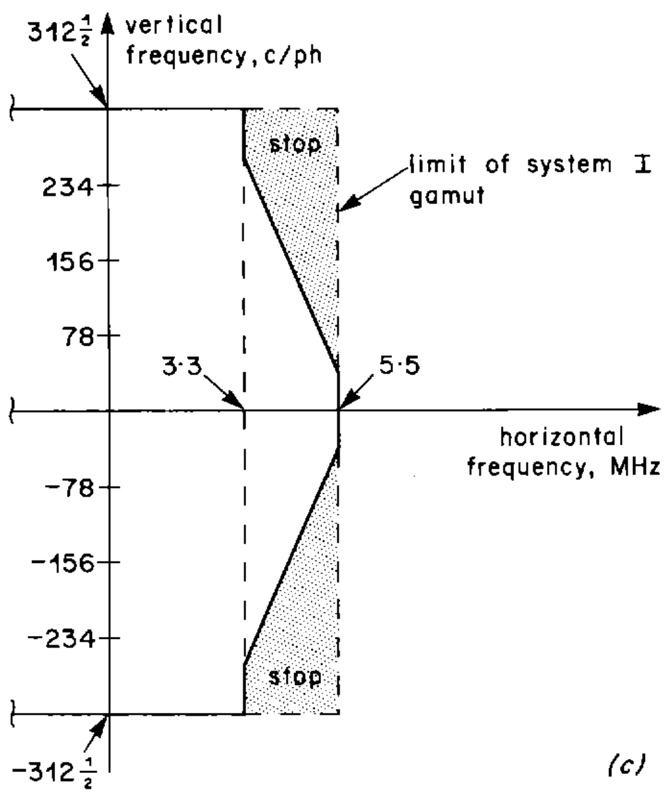


Fig. 5 — The idealised three-dimensional frequency characteristic of the luminance filter which packs the spectral energy closest to the origin.
(a) vertical-temporal cross section at the horizontal component of the subcarrier frequency.
(b) horizontal-vertical temporal cross-section along the line AB in (a).
(c) horizontal-vertical cross-section at zero temporal frequency.

MAC system[13] . When MAC had been chosen in 1982 by the Part Panel for DBS, an intensive investigation was mounted into ways of improving the vertical chrominance performance whose deficiencies had been apparent to the skilled observer in the trials. As MAC chrominance is based on line-sequential U and V it has similar properties to Clean PAL chrominance, based on line-sequential $U \pm V$, except that, in MAC, the vertical sub-sampling is reset after two fields. So an investigation into spatial processing of MAC chrominance on still pictures is also an investigation into Clean PAL chrominance except that the UV crosstalk components are stationary. Using electronically generated graphics it was possible to show the improvement in crosstalk performance conferred by the seventh order filters originally used in the Wells demonstration. Vertical resolution loss, compared with RGB, was now clearly visible on the most critical graphic material but the improvement over first-order filtering, used in the IBA's original MAC demonstration, was striking.

When consideration was being given to the form of the signal to be handled in the projected DBS studio and transmission centre, Clean PAL was proposed as one alternative since it offered the advantage of compatibility with existing studio equipment. However it was not chosen, even though its vertical chrominance resolution is a good match with MAC, because it was felt that the DBS Centre would be appropriate for a first service application of digital YUV signals in a studio infrastructure.

6. Proposals for future work

The principal objection to Clean PAL appears to be the loss of diagonal resolution, but this can be mitigated by the use of three-dimensional filtering. Picture-delay (i.e. pure temporal) filtering gives perfect resolution for stationary pictures with a 'just perceptible' loss on moving pictures, so it is quite likely that a compromise can be found which sacrifices a slight amount of diagonal resolution for acceptable motion performance. One approach is to construct a filter which maximises the spectral energy closest to the origin in three-dimensional terms, the three-dimensional counterpart of Fig. 2. In Fig. 2 the filter bounds perpendicularly bisect the lines joining the origin to the $2f_{sc}$ points, i.e. the $2f_{sc}$ vectors. In three-dimensions $2f_{sc}$ has a temporal component and the filter bounds become planes perpendicular to the $2f_{sc}$ vectors which are inclined to the pure spatial frequency plane as shown in Figs. 5(a) and (b). As a result, the pass region includes a better distribution of stationary luminance as shown in Fig. 5(c) when compared with Fig. 2. Bearing in mind that luminance frequencies beyond 156 cycles/picture height are confused by the aliasing of the field scan, the loss of diagonal resolution in Fig. 5(c) would probably be imperceptible; the lowest spatial frequency magnitude in any direction is still 5.5 MHz. On movement, the average performance of the filter is better than picture-delay filtering for frequencies below f_{sc} in exchange for a worse performance beyond f_{sc} .

Turning to the chrominance performance, this, too, can be improved by three-dimensional filtering. Preliminary assessment of three-dimensional chrominance filtering using a flexible real-time PAL decoder being developed by Clarke shows that a certain amount of chrominance temporal filtering can be tolerated. This contradicts the earlier observations of Wells, which could be explained by assuming that his observers were responding to cross-luminance rather than chrominance effects since the two could not be separated in his experiments. If chrominance can, to some degree, be temporally filtered then a correspondingly improved Clean PAL performance could be obtained by using a vertical-temporal chrominance filter as shown in Fig. 6. This still allows U and V to be combined into a single $U \pm V$ signal without interaction as shown. The resultant vertical bandwidth of the chrominance is now doubled in stationary areas compared with two-dimensional Clean PAL. This means that it is also double the MAC bandwidth (but MAC could also be doubled if it used a 4-field UV alternation period). Preliminary assessment, using the computer image processor, shows that limiting the chrominance to ± 156 cycles per picture height (as shown in Fig. 6) gives a 'just perceptible' impairment compared with RGB on the most critical graphic material; it is a great improvement in chrominance resolution over the vertical filtering used in MAC and in the Wells demonstration.

It must be stressed that these proposals for three-dimensional filtering are tentative at this stage. Much work needs to be done to establish what movement impairment can be tolerated subjectively using critical pictures. In addition, the compromise must be sought between filter complexity and level of luminance and chrominance aliasing, complexity at the receiving end being, as always, more economically important than at the sending end.

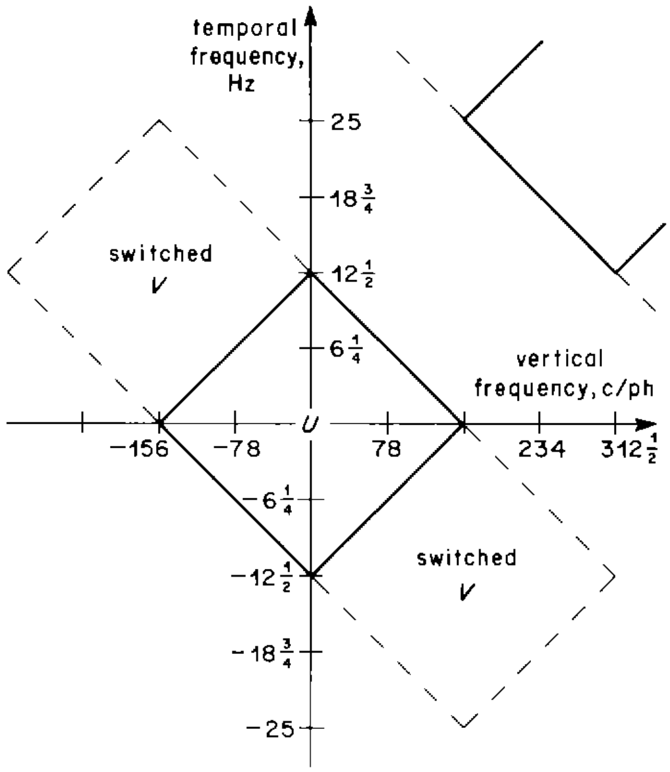


Fig. 6 — The vertical-temporal cross-section of the idealised three-dimensional frequency characteristic of a chrominance filter which balances vertical and temporal resolution.

7. Conclusions

The PAL system is far from being incapable of further development. Advantage can be taken of the redundancy which was built into it at a time when analogue links were of monochrome quality, to convey its three component signals with better spectral distribution and less interaction. The deficiencies of the earlier band-segregated proposals in which the components were allocated to separate spectral bands can be mitigated by using new methods relying on a quadrature relationship between luminance and chrominance so that their spectra may overlap. These methods enable twice the usable 'bandwidth' (in three-dimensional terms) to be recovered, and have been steadily developed since the new method was discovered.

Proposals are made here for systems based on complex filters involving field delays but these depend on the subjective acceptability of the temporal filtering so introduced on moving pictures. As it has been only recently possible to realise such filters, economically, much research needs to be done in this area. If such filtering proves acceptable the chrominance resolution on still pictures would be better than present day 'delay-line' PAL receivers and double that of the MAC system as proposed for DBS.

It may be many years before the implementation of such complex methods becomes economic at the receiver. In the meantime a cheap version of the decoder or even a conventional decoder would benefit from introducing the techniques at the coder although further research needs to be done to determine the extent of that benefit. Thus the proposals form a basis for the further evolution of the PAL system whilst remaining compatible with the present system.

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Printed by BBC RESEARCH DEPARTMENT Kingswood Warren Tadworth Surrey KT20 6NP